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SOLIFLUCTION, A COMPONENT OF SUBAËRIAL DENUDATION

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According to the theory of river development, as it has been worked out in its full modern form by a number of eminent American morphologists, the occurrence of narrow *v*-shaped valleys in a region indicates that the region in question has passed only the very first stages of the cycle of erosion. This type of valleys, considered by older European geologists as the most important feature of river-action, is, according to the modern American school, only an immature stage in the development of river valleys.

In the course of time the blocks of land left between the principal valleys will be dissected by secondary streamlets, the valleys will be broadened, and their slopes will get more and more gentle. At last, if the subaërial denudation has time enough to fulfil its work under unaltered conditions, the hills are wholly consumed, the region is base-leveled, and the land once deeply dissected is turned into a slightly undulating plain with broad and shallow, faintly insected river valleys. Not till then has the process reached the final stage of its cycle, the "peneplain."

This theory of subaërial denudation is based upon the premise that river-erosion works all over the *areas*, and not only *linearly*, as was supposed by an older school of geologists. This assumption looks at first somewhat startling. Evidently the main stream and the principal tributaries of a river form only a branching system of erosive *lines*. Only when the innumerable rivulets and feeders, all the transient small waters washing hillsides and slopes at rainfalls and snow-meltings, are taken into consideration, does the erosive system present a network so close that it can be said to cover all the area.

In its finest embranchments, in the region of the primal feeders, the erosive system is highly supported in its work by the weathering of the rock and by *a slow movement of the waste-sheet down the slopes*

The latter process, generally little estimated, has been clearly sketched by the master of the American "base-leveling" school, W. M. Davis:

> The movement of land-waste is generally so slow that it is not noticed. But when one has learned that many land forms result from this removal of more or less waste, the reality and the importance of the movement are better understood. It is then possible to picture in the imagination a slow wasting and creeping of the waste down the land slopes; not bodily or hastily, but grain by grain, inch by inch; yet so patiently that in the course of ages even mountains may be laid low. . . . . Every change of condition between cold and warm, dry and wet, melted and frozen, that causes a gain or a loss of volume in the rock-waste aids its slow movement down-hill. With countless minute changes every particle is led, slowly but surely, from higher to lower ground.[1]

It seems to me that it is in the removal of the waste, by which the undecayed rock is again exposed to the attack of the weather and the débris is carried to the primal streamlets, that this process, in its more or less rich development, chiefly determines the effectiveness of river-action in peneplaining. Professor Davis supposes that the removal of the waste may continue also underneath a cover of vegetation, and he points out that "the growth and decay of plant roots aid the downward creeping of the waste." But experience has taught us that in regions covered by a rich vegetation the removal of the débris must be very slow, as the unaltered rock is, in most cases, hidden by a deep covering of decayed material. In those lands where the climatic conditions are unfavorable for the removal of the waste the material carried away by river transport must be comparatively scarce and the subaërial denudation only very slow in its advance toward its final end, the peneplain.

But, on the contrary, in regions where the vegetation, because of the hostility of the climate, is all too scarce to fix the detritus, but when the precipitation is still abundant enough to cause effective action by running water, a quick removal of the waste and a plenteous feeding of the streamlets with detritus highly accelerate the subaërial denudation.

During the last few years I have had opportunity of studying, under high northern and southern latitudes, regions where the removal of the waste is now going on under peculiar conditions, and in another case was working during a bygone climatic depression in a most effective manner almost all over the area of the islands under consideration.

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[1] Davis, *Physical Geography*, pp. 263, 267.

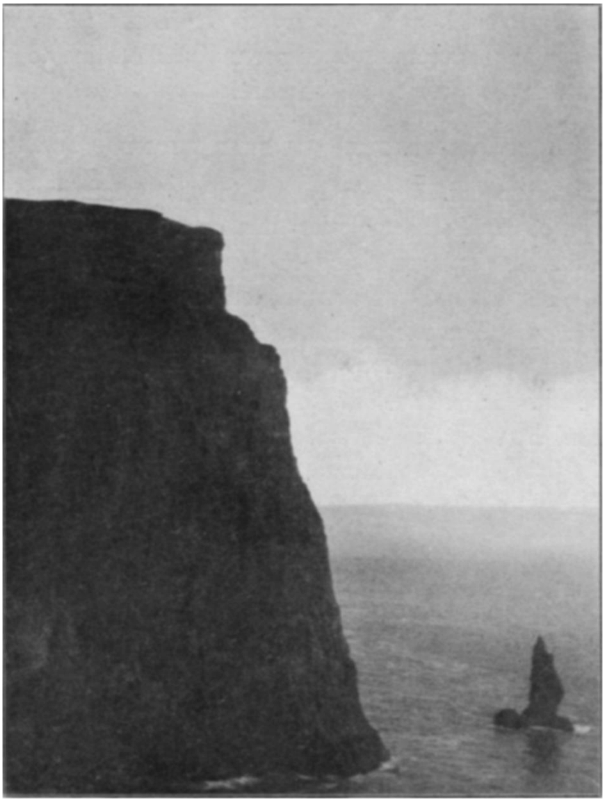

Fig. 1.—Bear Island. Sea cliff, 400 meters in height.

I have thought it possibly useful to publish a short preliminary review of my observations, as they may add to the understanding of an important component of subaërial denudation. The phenomenon I am going to describe is by no means new to science; on the contrary, it has been noticed and clearly described by many skilled observers from different parts of the world, where the conditions are favorable for its development. But it seems to me that there has been a tendency to depreciate its importance as a link in the series of denudative agents, and to look at it as only a curiosity of mere local nature. No one, as far as I know, has collected the scattered material, as I will try to do in the following pages, and probably few have had an opportunity like mine to study the phenomenon in its fullest development.

SOLIFLUCTION IN BEAR ISLAND

This islet situated in 74½° N. L., in the Atlantic part of the Arctic Ocean, is a small remainder of a once larger stretch of land. Sea cliffs, in some places rising to the height of 400 meters and fringing the island almost all around, tell us of the destructive action of the abrasion. The northern and larger part of the island forms a lowland plateau rising very slowly from the recent coastal outline to the interior and cut out through slightly dislocated Devonian and Carboniferous beds. Several reasons, among others the occurrence of old, somewhat obliterated coastal cliffs at the inner margin of this plateau, incline me to consider it as worked out by marine abrasion.

The southern part of the island is mountainous, with tops rising to 460–539 meters. In this region the ground is composed of a great variety of sedimentary rocks from Silurian to Triassic age, and the older strata are cut up by vertical dislocations into a few parallel blocks. In some cases the denudation has laid bare parts of the precipitous surfaces of the faults, but as a rule the land-sculpturing agents show a marked tendency to smooth the tilted blocks to rounded hills and broad river valleys with gentle slopes. Thus the land forms of the interior of the island are in a striking contrast to the perpendicular cliffs on the sea side.

On the hill-slopes and valley sides of Bear Island there are almost everywhere clear indications of a moving of the waste from higher to lower ground. Many of the small hills show a very marked streakiness of surface, which is due to the peculiar arrangement of the detritus; sometimes the flowing soil forms real streams which have much likeness to a glacier in miniature, and often in the depressions between the hills there are numerous small circular or semicircular walls composed of rock fragments and including a patch of muddy material, often hardened through desiccation. Evidently all these phenomena only represent different facies of the displacement of the waste.

It is not very difficult to find out the mode of formation of the "mud-glaciers" mentioned above. When in summer time the melting of the snow has reached an advanced stage, often the bottom of the valleys are free from snow, while big masses still rest in sheltered places on the valley sides. Every warm and sunny day new quantities of water trickle from these melting drifts into the rock-waste at their lower edge. As the masses of detritus are composed not only of coarser rock fragments such as blocks, slabs, and gravel, but also of finer particles filling the interspaces between the coarser material, they are able to absorb considerable quantities of water. When once saturated, they form a semifluid substance that starts moving slowly down-hill. This process, the slow flowing from higher to lower ground of masses of waste saturated with water (this may come from snow-melting or rain), I

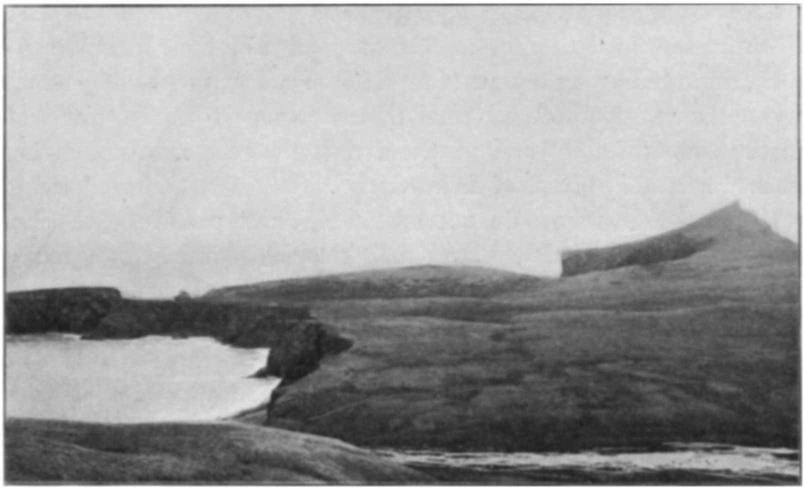

FIG. 2.—Scenery from the southern part of Bear Island, showing the contrast between the rounded land-forms caused by subaërial denudation and the perpendicular coastal cliffs caused by marine abrasion, dissecting the island.

propose to name *solifluction* (derived from *solum*, "soil," and *fluere*, "to flow").

As the snowdrifts of Bear Island diminish in the course of the summer, new ground is exposed, its waste is thawed, and then, saturated with water, it follows the slow downward movement. The flowing detritus does not generally move as a "sheet-flood" with a broad front, but more often flows in some slight depression of the slope, taking the form of a narrow tongue, offering a most striking parallel to a glacier. The névé region is represented by the area of water-saturated detritus at the lower edge of the melting snowdrift, and the flowing tongue of mud is the glacier proper that moves down the valley. The terminal moraine even is often to be seen in the shape of slabs and pieces of rock that the mud-stream has pushed together in front of its lower end.

These mud-streams do not consist of finer particles only, but also of coarse material, gravel and blocks, frequently intermixed with, and also carried on the top of the muddy substance.

Small mud-glaciers of the type just described are very common in Bear Island, and sometimes they reach noticeable dimensions. On the slope of Oswald Hill I measured such a tongue of detritus that had a breadth of 35 meters and a depth (thickness) of at least 2.1 meters. In this case "the terminal moraine" was represented by a zone of sandstone plates, pushed together so that they were all standing edgewise beautifully concentric to the rounded front of the detritus tongue, and this piled-up zone had the rather startling width of 17 meters! This example may give some idea of the considerable quantity of detritus that can be removed in a single stream, as well as of the energy which such a mud-glacier can develop before its movement is arrested.

My companion in the voyage to Bear Island, Dr. G. Swenander, during his botanical researches made an observation that was highly illustrative for a proper understanding of the extent and importance of the solifluction.

Bear Island looks very barren also when compared with more northern Arctic islands, and its sterility is proved not only by the small number of species of higher plants, but also by the complete barrenness of large areas

Swenander gave an explanation of this scantiness of the flora: All the phanerogamic plants of Bear Island—with the exception of a single species—are perennial, and these forms cannot endure upon the flowing soil, where they are easily drowned in the moving mud. The sterility of the areas of solifluction is quite a striking feature of the island. On many slopes small hills of the solid rock crop out of the covering of moving waste, and, though the soil is very scant in the small fissures and crevices of the rock, here the plants grow more willingly than upon the perfidious flowing ground. Thus these small rocky hills form cheerful verdant patches scattered over the barren slopes. In the rare cases when Swenander found single plants growing upon the moving waste, he could demonstrate a remarkable adaptation to this mode of life. The root system of these specimens was exceptionally developed in order to keep the plant afloat on the moving medium. These roots were stretched out in the direction of the movement of the soil, and in some cases where the slope was very steep it was noticed that the proximal part of the root system, carried by the more rapid flowing of the superficial layer of the mud-stream, had reached a *lower* level than the distal branches, which, joining the slower movement of deeper parts of the stream, were left behind in the displacement down-hill. These facts, which I owe to my friend Dr. Swenander, illustrate better than anything else the mode of progress and the importance of solifluction in Bear Island. Evidently, then, this process is a chief agent of the denudation. Every summer large masses of detritus in this way flow down-hill into the bottom of the valleys, where the streamlets undertake the work of transport. It is characteristic for this hitherto undervalued component of subaërial denudation, which I have named "solifluction," that—in contrast to the wind and the running water—it does not lift its material, but like the glacier-ice—with which it has been already compared—it removes blocks and gravel almost as well as the fine mud.

THE STONE-RIVERS OF THE FALKLAND ISLANDS

This island group, situated in 52° S. L. in the South Atlantic, consists of two large and a great number of small islands. The East Falklands, and to some extent also the western large island, present an undulating land surface built up by slightly folded Devonian beds and evidently subjected for a long time to subaërial denudation. With the exception of some resistant quartzite ridges, they, and especially the eastern island, are far advanced toward the peneplain. The land is woodless over large areas, and occupied by peat-bogs, the drier places forming grass steppes and the very driest heaths covered by *Eupetrum rubrum.*

This landscape, as bewildering through the monotony of its outlines as deterring through its ugliness, boasts a natural phenomenon that may be unparalleled in the world. The "stone-rivers," which form a beloved object of the fancy of the population, were lucidly described by Charles Darwin, though he could not find a satisfactory explanation; but a later visitor, Sir Wyville Thomson, got very near to a proper understanding of the thing. In order to demonstrate the process in question, I quote the condensed description given by the eminent naturalist of the "Challenger:"

> In the East Island most of the valleys are occupied by pale gray glistening masses, from a few hundred yards to a mile or two in width, which look at a distance much like glaciers descending apparently from the adjacent ridges, and gradually increasing in volume, fed by tributary streams, until they reach the sea. Examined a little more closely, these are found to be vast accumulations of blocks of quartzite, irregular in form, but having a tendency to a rude diamond shape, from two to eight or ten or twenty feet long and perhaps half as much in width, and of a thickness corresponding with that of the quartzite bands in the ridges above. The blocks are angular like the fragments in a breccia, and they rest irregularly one upon the other, supported in all positions by the angles and edges of those beneath.[1]
>
> There can be no doubt that the blocks of quartzite in the valleys are derived from the bands of quartzite in the ridges above, for they correspond with them in every respect; the difficulty is to account for their flowing down the valley, for the slope from the ridge to the valley is often not more than six to eight degrees, and the slope of the valley itself only two or three, in either case much too low to cause blocks of that form either to slide or to roll down.
>
> The process appears to be this: The beds of quartzite are of very different hardness; some are soft, passing into a crumbling sandstone; while others are so hard as to yield but little to ordinary weathering. The softer bands are worn away in process of time, and the compact quartzites are left as long projecting ridges along the crests and flanks of the hill ranges. When the process of the disintegration of the softer beds has gone on for some time, the support

[1] Thomson, *The Atlantic*, p. 245.

> of their adjacent beds is taken away from the denuded quartzites, and they give way in the direction of the joints, and the fragments fall over upon the gentle slopes of the hillside. The vegetation soon covers the fallen fragments, and usually near the sloping outcrops of the hard quartz, a slight inequality only in the surface of the turf indicates that the loose blocks are imbedded beneath it. Once imbedded in the vegetable soil, a number of causes tend to make the whole soil-cap, heavy blocks included, creep down even the least slope. I will only mention one or two of these. There is constant expansion and contraction of the spongy vegetable mass going on, as it is saturated with water or comparatively dry, and while with the expansion the blocks slip infinitesimally down, the subsequent contraction cannot pull them up against their weight; the rain-water trickling down the slope is removing every movable particle from before them; the vegetable matter on which they are immediately resting is undergoing a perpetual process of interstitial decay and removal. In this way the blocks are gradually borne down the slope in the soil-cap and piled in the valley below. The only other question is how the soil is afterwards removed and the blocks left bare. This, I have no doubt, is effected by the stream in the valley altering its course from time to time, and washing away the soil from beneath.[1]

This explanation given by Sir Wyville Thomson, referring the formation of the stone-rivers to the slow removal of the waste down the slopes, must be willingly accepted by everyone who has studied the "stone-runs" in nature. The only objection, and that a very essential one, is against the idea of the phenomenon as a product of present conditions and of the process as still working with full effectiveness underneath the vegetation that now partly covers the stone-rivers. It ought to be noticed that long before I visited the Falkland Islands and studied in detail one of the stone-rivers, James Geikie, knowing these tracts only from the descriptions of Darwin and Thompson, had already expressed the opinion that the stone-runs were comparable to the rubble-drifts of England, or otherwise that they were formed in a bygone period, characterized by a climate more severe than the present.[2]

When I came to the Falkland Islands in 1902, I did not know of the ingenious comparisons made by James Geikie, but with my earlier experience from Bear Island it was easy to go straight to a full understanding of the thing.

Solifluction, in its quite typical form, is still at work in the Falkland Islands, but only on a small scale in favorable localities where

[1] *Ibid.*, pp. 246–48.

[2] Geikie, *The Great Ice Age*, 3d ed. (London, 1874), pp. 722, 723.

the hillsides are steep, the vegetation scarce, and the trickling water saturates the soil.

On the slope of Stephens Peak, a conical sandstone hill on the south coast of West Falkland, I found a recent mud-stream extending almost from the top of the mountain to its base, with a breadth of 32 meters where it was widest. The fall of the stream was 11–19°. Its material was a kind of stony clay charged with big blocks, the whole having much resemblance to some types of the glacial till. Also on the surface of the stream there lay numerous blocks, the largest having a diameter of 1.5 meters. I removed several of these big blocks to examine their bedding, and I always found them to rest upon the stony mud, never upon a basement of other blocks or solid rock.

In other parts of the same slope I found ancient mud-streams which were bordered by vegetation and evidently fixed at the present time. In some places the fine material was washed away by surface water, only to leave a residuum of sandstone blocks, a copy in miniature of the large stone-runs. Between the latter and the recent mud-streams of Bear Island my observations on the slopes of Stephens Peak gave all the transitional stages.

But although the solifluction is still working in exceptionally favorable places in the Falkland Islands, it seems to me quite evident that the large stone-runs, which are covered with vegetation in all places where the fine material is not washed away, were formed in an earlier period, when the solifluction was working in this region upon a much larger scale than today. Apparently several changes in the level of the land and in the condition of the climate have passed over these wonderful, timeworn giants.

I have studied in detail, and surveyed in the scale of 1:20,000, the big stone-river (possibly the largest in the islands) south from Port Louis, which was originally described by Darwin. In a coming paper I will publish this material *in extenso*, but for the present purpose the following brief remarks may be sufficient.

The open areas and strips consisting only of a chaotic accumulation of large blocks of quartzite evidently have been formed by a secondary washing away of the finer material that once filled all the interspaces between the big blocks or carried parts of them on its surface. As will be demonstrated by my map, the contours of these vegetationless block-fields, with all their embranchments, give the rude outlines of a small river system, and, as has been mentioned already by Darwin and Thompson, in many places the purling of running water is heard far down below under the blocks, indicating the recent course of a stream in the depth of the stone-river.

But the real extent of the ancient *flowing slopes* is much larger than that indicated by the open vegetationless block-fields. In all places where running water has not washed away the fine material the old detritus flows remain in their original composition and offer a soil which is able to carry a covering of vegetation. Where there is a small cut of any kind in such an unaltered part of the slope, it is easy to recognize that the mass underneath the mantle of vegetation is the same as in the waste-streams on Stephens Peak, large blocks imbedded in fine rock detritus.

The large old stone-runs of the Falkland Islands evidently were formed in a period of the past with a climate more severe than the present, with heavy snowfalls in winter, but also with summers characterized by active snow-melting, causing an intensive solifluction which was ever victorious in the fight with the then poor and scattered vegetation. I fancy that in these days the state of the Falkland Islands was very much like that which I have actually studied on the Bear Island of today.

It is very inviting to connect this birthtime of the Falkland stone-rivers with the great climatic depression of a bygone time that has been demonstrated in the adjacent southern lands.

In Tierra del Fuego and the south part of Patagonia Darwin, Agassiz, and O. Nordenskjöld have studied the moraines of an old land-ice extending to the Atlantic Ocean, in South Georgia I have traced a complete glaciation of the island, and in the Antarctic region, in Graham Land, Arctowski, Nordenskjöld, and myself have found full evidence of an earlier, much larger extension of glaciers and land-ice.

To the west, east, and south the Falkland Islands are surrounded by lands deeply furrowed by an old ice age. In our islands, on the contrary, there are no traces of an old ice-sheet, no grooving of the rock-surface, no moraines, and some very characteristic relief forms are directly incompatible with the hypothesis of an earlier ice-action upon the islands.

But, on the other hand, it seems impossible that the great wave of cold, which has set its mark so severely upon the surrounding lands, should have left no traces on the Falkland Islands. Nothing is then more natural than the presumption that the birth of the stone-rivers is a facies of the ice age of the southern lands. In the Falkland Islands the climatic depression was not severe enough to cause a glaciation, but only an intensive frost-weathering and flowing slopes, quite as today in Bear Island we have no glaciers, but only a marked solifluction.

The stone-rivers certainly are the most striking feature of the inland scenery in the Falkland Islands. Never did I feel them more imposing than in a voyage along the southern coast of East Falkland. Then, behind the lowland forming the south part of the island, I saw in the distance the Wickham Heights, the principal watershed, in its full extent. Every transverse valley of the low mountain range was filled by the gray mass of a stone-river extending to or upon the lowland at the mountain's foot. The resemblance to a region crowded by valley glaciers was really amazing.

The unsurpassed grandeur of the Falkland stone-rivers was sufficient to provoke the idea that in this island group the solifluction has been at work on a larger scale than anywhere else on the present earth surface. But I think that this effect of the solifluction, that we meet with in the stone-runs, is rather exceptional, depending upon the petrological character of the rock yielding the material to them.

As already cited, Sir Wyville Thomson has clearly described how the mountain ridges, from which the stone-rivers flow, consist of hard, thick quartzite-bluffs, with intercalations of more soft material. The last-mentioned softer bands are successfully attacked by the weathering and turned into a muddy mass forming the matrix of mud-streams. The quartzite bluffs, thus deprived of their footing, break down in big blocks, and these are carried down-hill by the mud-streams. In the bottom of the valley the fine material is removed by running water, and there is left a very abundant residuum of huge, hard quartzite blocks, almost unattackable by weathering. Such a result of the combination of solifluction and river-action will be reached only with rocks com posed of an alternation of soft and extremely unattackable material. In other cases also the big blocks will gradually succumb to the weathering, the river will be able to clear its course. and new mud-streams will follow those already washed away by the running water.

Also in this respect a comparison with the conditions of Bear Island is highly instructive. In the southern, mountainous part of the island, where I have studied the solifluction in its most varied development, and where the ground is for the larger part composed of rocks (slates, limestone, dolomite), which are through all its mass almost uniformly attackable by weathering, I have found, in the course of the small rivers, no accumulations of big, irregular blocks like those of the stone-rivers. But as soon as one enters the areas of the Ursa sandstone—a rock in parts much like the sandstone of the Falkland Islands, and consisting of alternating hard quartzites and soft intercalations—the aspect of the ground is quite altered. The vast Ursa sandstone area on the flat land in the north of the island is all densely covered over with huge, edged blocks, the whole forming a regular Gehenna for the wanderer—quite as the stone-rivers.

I feel sure that these immense block-fields of Bear Island are formed in quite the same manner as the Falkland stone-runs: by weathering of the rock; by solifluction (though this is very slow and hardly perceptible in the great plain of Bear Island); finally also by the action of running water. The only differences between the two occurrences are differences of topography and of age: in Bear Island a great plain forming a *stone-field*, in the Falkland Islands valleys filled at the bottom by *stone-rivers*—the former a recent, the latter a fossil occurrence.

According to the relation given above, the Falkland Islands are characterized not so much by the extreme intensity of the solifluction in a past time as by an exceptional abundance of the residuum left by the running water that has sifted the material of the old mud-streams. Under other petrological conditions the result of the combination of solifluction and river-action will be, not the formation of stone-rivers, but—if the time of their action has been long enough—the leveling of the land to peneplain.

REGIONAL EXTENSION OF THE SOLIFLUCTION

From Bear Island in the arctic and from the Falkland Islands in the subantarctic regions I have described in the previous pages two occurrences of solifluction—one recent, the other fossil—where in both cases the phenomenon is developed in rather exceptional dimensions. But, if often only in a moderate scale, this mode of waste transport works in many parts of the world. In the geological, geographical, and botanical literature there are to be found many notes on mud-streams and flowing slopes, illustrating the process here in question. In the following pages I have collected, partly with the assistance of helpful friends, some descriptions of of soil-flowing, but the list of them is given without any pretentions to completeness. Surely many a valuable note on processes of this kind has escaped me, and I hope that colleagues in different lands, after having read this article, will kindly call my attention to observations still unknown to me.

South Georgia.—This subantarctic island is a ridge of folded land, deeply indented by transverse fiords between which the mountains rise steeply to 1,000–2,000 meters. Small glacier caps of varied type occupy a large part of the mountains, and in many of the valleys splendid glacier streams extend into the fiords. But the narrow lowland strips and much of the mountain slopes were free from ice-covering, and here frost-weathering, solifluction, and running water are the chief agents of destruction. Slowly moving slopes and small mud-streams were frequently seen, and the forms of the detrital masses offered many a striking parallel to my earlier experiences on Bear Island.

Graham Land.—The ice-covering of the antarctic lands is all too complete to leave any place for solifluction on a large scale; but on the very limited areas where the land was exposed we could trace almost everywhere this mode of transport working in the summer. On the plateau above the winter station on Snow Hill, Nordenskjöld kindly pointed out to me a locality where the land surface showed the same streakiness that I had seen before in Bear Island, beautifully developed, and which was evidently due to displacements of the soil.

North America.—I have had no time for looking into the immense American literature for notes indicating observations on solifluction, and shall be most thankful for any information on this subject relative to that continent where the land forms are so splendidly developed and so admirably surveyed.

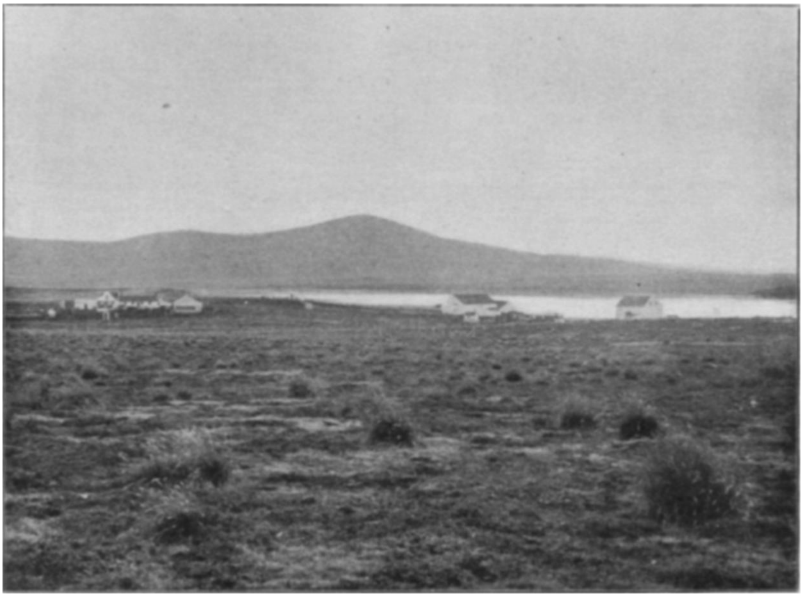

FIG. 3.—Fox Bay, West Falkland. Scenery showing the vast plains and the low, rounded mountains.

The only observation from the United States that I am able to mention here is cited by James Geikie in *The Great Ice Age*, and is taken from Hayden, who has given a very illustrative description of solifluction in some valleys in the Rocky Mountains. These valleys are

> covered thickly with earth, filled with more or less worn rocks of every size, from that of a pea to several feet in diameter. The snow melting upon the crests of the mountains saturates these superficial earths with water, and they slowly move down the gulch much like a glacier.[1]

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[1] *Geological and Geographical Survey of Colorado*, 1873, p. 46.

A note on "flowing soils" is also cited by James Geikie[1] from the arctic part of the American continent. The observation was made by Sir Edward Belcher on Buckingham Island in 77° N. L. He ascended a hill 200 feet above the sea to make observations, and found the soil well frozen and firm and covered with a slight crust of snow. But as the power of the sun increased toward noon, the snow disappeared.

> As noon passed the soil in all the hollows or small watercourses became semifluid, and very uncomfortable to walk on or sink into. At the edge of the southern bank the mud could be seen actually flowing, reminding one more of an asphalt bank in a tropical region than our position in 77[1] 10′ N. The entire slope, in consequence of the thaw, had become a fluid moving chute of débris for at least one foot in depth.[2]

Spitzbergen.—During the arctic expedition of 1898, under the command of Professor A. G. Nathorst, when I made my first acquaintance with the solifluction in Bear Island, I also had opportunity to see some phenomena of this kind in Spitzbergen, where they were studied somewhat more in detail in the neighborhood of Hecla Cove, in Treusenberg Bay by my companions G. Andersson, H. Hesselman, and A. Hamberg. The following year, 1899, Dr. Th. Wulff made some observations on the same phenomenon in the first-named place and in Green Harbor in the Ice Fiord.[3]

Recently Professor DeGeer has given a brief account of his researches on moving slopes made during several expeditions to Spitzbergen, partly long before the observations mentioned above.[4] DeGeer has noticed the phenomenon in several localities in the Ice Fiord region, as at the Wahlenberg glacier, at Temple Bay, where the cover of vegetation had got dispersed by a mass of moving soil, and at Cape Thordsen. At the last-mentioned place a small railroad was built many years ago (1872) for mining purposes. Ten years later the railroad could still be used, but in 1896 De Geer found it to be greatly distorted by the effect of the moving soil.

De Geer points out that the waste-sheet generally moves over a bedding of frozen soil, and that also regelation may act in the displacement of the moving masses.

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[1] *Op. cit.*, pp. 387, 388.

[2] *The Last of the Arctic Voyages*, Vol. I, p. 306.

[3] Th. Wulff, *Botanische Beobachtungen aus Spitzbergen* (Lund, 1902), pp. 85, 86.

[4] *Geologiska Föreningen i Stockholm Förhandlingar*, 1904, pp. 465–66.

Scandinavia.—From the mountainous region of Valders in Norway H. Reusch has given a very interesting description of solifluction.[1] To judge from his sketches and verbal testimony, the phenomenon here is very similar to what I have studied in Bear Island, though not so largely developed.

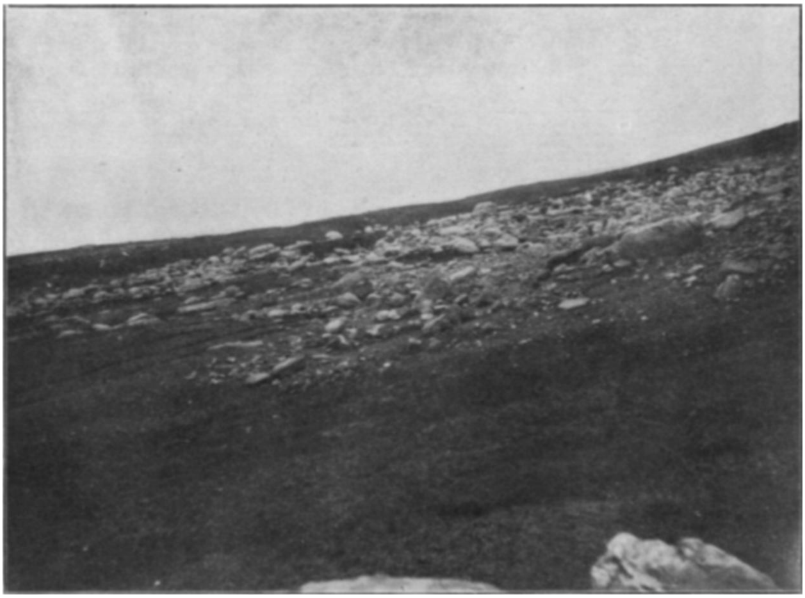

FIG. 4.—Recent mud-stream charged with big blocks. Stephens Peak, West Falkland.

From Sweden a considerable number of notes on solifluction have been published quite recently, after my lectures on the flowing slopes of arctic and sub-antarctic islands had directed the attention of our geologists to the problem.

R. Sernander has given some very important observations from Häijedalen, commenced in 1895 and largely supplemented in the summer of 1904.[2] In the places studied by him, and as a rule in all parts of the mountain regions of Sweden where the process has been noticed, it has given origin only to small narrow terraces, not to far extended mud-streams—a difference possibly indicating that the solifluction here works with less intensity than in the tracts studied by me.

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[1] *Norges Geologiske Undersögelse, Aarbog,* 1900, pp. 75, 76.

[2] *Geol. Fören. i Stockholm Förh.,* 1905, pp. 42 ff.

Detritus terraces of the type mentioned have been noted by De Geer on the Ovik Mountains in Jämtland, and by Svenonius at Sitasjaure and Vassijaure in Swedish Lappland.[1]

All these observations are made in the high mountain regions, but Professor Högbom has, in a very interesting paper, called attention to the fact that under favorable conditions solifluction can work on a rather large scale also in the woody lowlands of Norrland, and in some rare cases also in more southern parts of Scandinavia. Högbom describes from Lule River how forest trees growing on slowly moving ground are deformed, and he clearly demonstrated that in the fine fluviatile sediments, filling the lower parts of the large river valleys in Norrland, soil-flowing in some places is a very important transporting agent.[2]

Tibet.—In the vast Tibetan highlands Dr. S. Hedin during his last expedition underwent most trying experiences of solifluction. For days and weeks his caravan struggled through a terrible quagmire of water-saturated detritus. Many a time the animals were brought out of the treacherous soil only with the utmost difficulty, and once a camel got lost in such a morass. "The poor beast was literally swallowed up in the mud, and all attempts to get him out failed."[3]

The descriptions by Hedin clearly show that the saturated soil actually moves down-hill, and that the solifluction in those far-extended highlands works on a very large scale, lowering the mountains and filling the valleys:

> I could not help thinking that the whole bunch of hills would, like a viscous fluid or thick porridge, gradually flatten themselves out to a uniform level. This conformation was caused by the incessant precipitation searching into the ground and making it like a sponge; for only a very small quantity trickled into the superficial brooks and rivulets, and so flowed away. The absence of vegetation with its interlacing roots also contributed to the same result. In two or three places *the shales stuck up edgewise* and cut the camel's feet.[4]

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[1] *Geol. Fören. i Stockholm Förh.*, 1904, p. 466.

[2] *Ibid.*, 1905, pp. 19–36.

[3] S. Hedin, *Central Asia and Tibet*, Vol. II, p. 288.

[4] *Ibid.*, Vol. I, p. 519. Italics are mine.

> The slope consisted of a gigantic sheet of mire, of the consistency of porridge, and to judge from the cracks which ran across it and all round it, the entire mass was slipping slowly, though imperceptibly, down the mountain-side.[1]

All the notes collected in the preceding pages deal with regions of *recent* solifluction. But of *fossil* occurrences of the same kind indications are to be found in the literature.

In the southmost part of England, outside the area of maximum glaciation, there is widely distributed a peculiar kind of deposit known by the name of "rubble drift," "head," etc., and consisting "of a more or less coarse agglomeration of angular débris and large blocks set in an earthy matrix."[2] This kind of soil is described from Cornwall and Devon, from the South Downs and from Guernsey, one of the Channel islands. According to the opinion of James Geikie and other English geologists, these beds were formed principally by solifluction as an extra-marginal facies of drift at the time of the maximum glaciation.

A deposit of the same kind is the massive breccia of Gibraltar, described by Sir A. C. Ramsay and James Geikie. It is a rude accumulation of angular fragments of limestone, of all shapes and sizes, imbedded in a calcareous grit and earth. As to its formation Geikie writes: "When the snow melted in summer, the rubbish, becoming saturated, would move forward *en masse*, like the so-called earth-glaciers of the Rocky Mountains, as described by Hayden."[3]

It is remarkable that there are two different horizons of limestone breccias at Gibraltar, indicating two separate epochs of severe climate.

After hearing my description of the Falkland stone-rivers and the explanation of them as a facies of the ice age, Professor Högbom called my attention to occurrences of the same kind in the Ural Mountains.

They are mentioned by Tschernyschew in *Guide des excursions des VII. Congrès géologique international*, Vol. III, pp. 28, 29; when describing the quartzite mountains in the environments of the mines of Bakalsk:

[1] *Ibid.*, Vol. II, p. 286.

[2] Geikie, *The Great Ice Age*, p. 389.

[3] Geikie, *op. cit.*, pp. 599, 600.

> Leurs versants sont couverts d'énormes éboulis des mêmes grès et quartzites, rendant très possible l'accès du sommet. Les amoncellements de grès d'un blanc de neige et de quartzites qui descendent dans les vallées latérales, offrent un aspect très original; de loin ces trainées, de pierres ressemblent de vrais cours d'eau, tant le caractère de leurs sinuosités rappelle les véritables torrents.

One of these Ural stone-rivers is figured in Ratsel, *Die Erde*, Vol. I, p. 479, this figure showing a complete resemblance to the Falkland stone-runs, only with the exception that the Ural stone-river is bordered, not by a grass steppe, but by pine forest. According to a communication given by Högbom, the region of the Ural stone-rivers lies outside the area of earlier glaciation. Nothing is then more natural than to explain also these formations as an extra-marginal equivalent to the ice-sheet.

To this account of fossil occurrences of solifluction we must add that Sernander in the mountain region of Härjedalen has found evidence of a considerably larger extent of the flowing soil in a bygone past of the postglacial epoch.[1]

The study of the traces of solifluction in earlier times is highly attractive, and of great importance for the understanding of the climate of the past and for the explanation of the chronology of the Quarternary period in extra-glacial regions. But these are problems which lie outside the scope of this article, and which, moreover, I will treat in detail in a paper on the geographical development of the Falkland Islands.

CONCLUSIONS

From the evidence given in the preceding pages it is easy to recognize the climatic features which form the optimum of the solifluction. In the polar and subpolar regions, where the ground is not covered with ice, we find this process working with more or less intensity almost everywhere, and in the same manner, the alpine tracts of lower latitudes are favorable for the development of this phenomenon. In these regions, characterized by a "subglacial" climate with heavy deposits of winter snow melting in summer, solifluction is a chief agent of destruction. The unceasing succession, summer after summer, of mud-streams and

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[1] *Geologiska Föreningens Förhandlingar*, 1905, pp. 42–84.

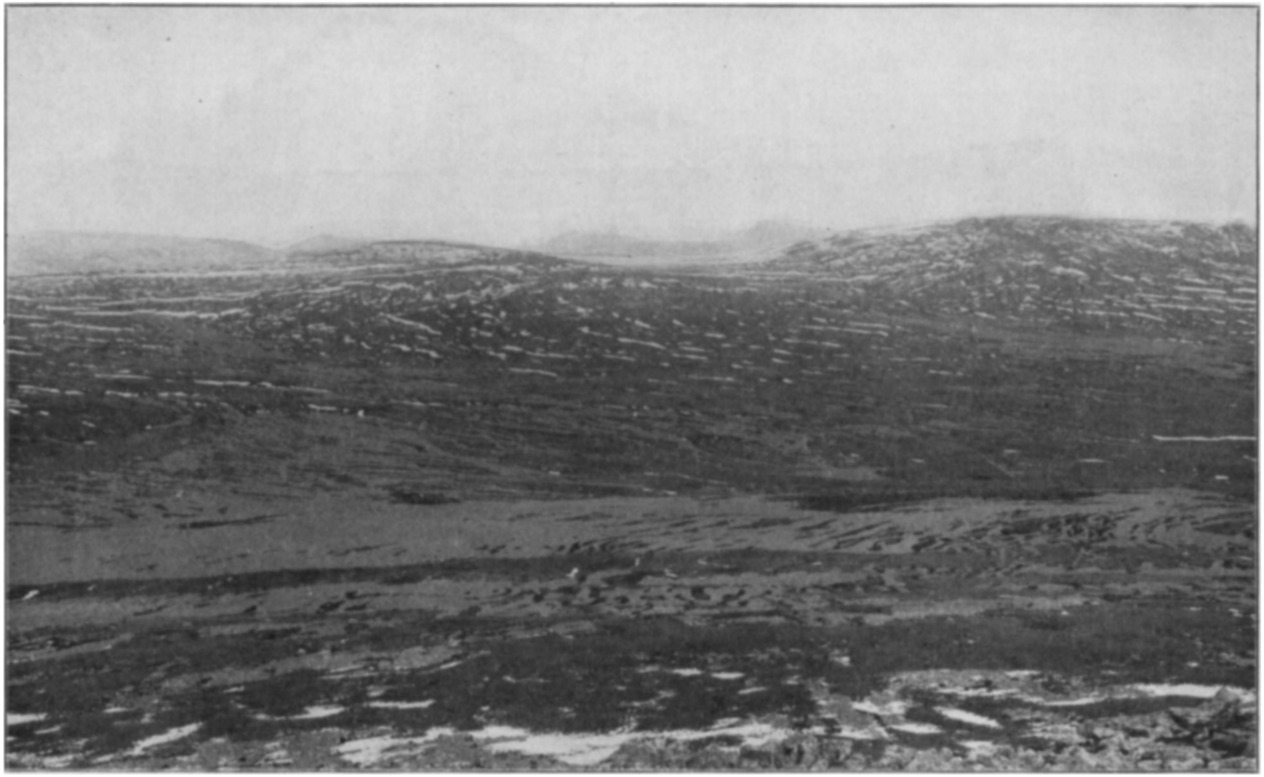

FIG. 5.—Part of the large stone-run south from Port Louis, West Falkland.

The light-gray mass in the bottom of the valley is the open block field, consisting only of a chaotic accumulation of big blocks. The dark narrow strips are covered by a vegetation of *Empetrum rubrum*. In these strips, as well as in the areas (dark gray on the photograph) covered by grass vegetation, fine material still fills the interspaces between the big blocks. The maintenance of unaltered strips in the largely washed block-field must be due to the original arrangement of the once slowly moving masses. Thus these strips of *Empetrum* and grass give clear indications of the direction of the movement in the old flowing slopes. From small transverse valleys in the background minute stone-runs descend into the principal valley, and here a real network of open block areas and grass patches gives to the eye in the distance a most wonderful imagination of a semi-fluid mass investing the valley. The photograph being taken in winter, the mountain hills are partly snow-covered.

moving slopes indicates that here the removal of the waste runs on at a rate that may be unsurpassed in other parts of the earth's surface—except in the deserts.

But this effective removal of the waste must be balanced on the one hand by a rapid production of new waste, and on the other, by an effective clearing out of valley bottoms by running water. The "subglacial" climate is most favorable for both these processes. In the extra-glacial regions the frost-weathering works with an intensity well known to every student of polar lands and alpine mountains, and the violent summer floods caused by the melting of the winter's snow give to the rivers of these regions an erosive power that is quite surprising.

When all these conditions are taken into consideration, the "subglacial" climate must be looked on as an optimum of destructive action. In fact, the high mountains, the large folded ranges, where all the agents mentioned work in high intensity, are found to be short-lived features in the earth's surface. In fact, one might be tempted to raise the question whether complete peneplanation is possible in regions where the action of running water is not supported by an effective removal of the waste, such as is produced by solifluction. With this premise, every peneplain found a climatic token of the same kind as the stone-rivers of the Falkland Islands and the limestone breccias of Gibraltar. Still I think that such a presumption hides a dangerous exaggeration. It is very possible that in many cases, under other climatic conditions of less erosive power, the process has had time to reach, though at a very slow rate, the end of the cycle of erosion.

But, on the other hand, it seems certain that solifluction has often been an important agent toward peneplanation. The importance of the process, because of its humbleness, has been much undervalued. But I feel sure that it is not until we get a knowledge of all the contributive agents that we can reach a full understanding of all the varied and complicated forms of land-sculpture.